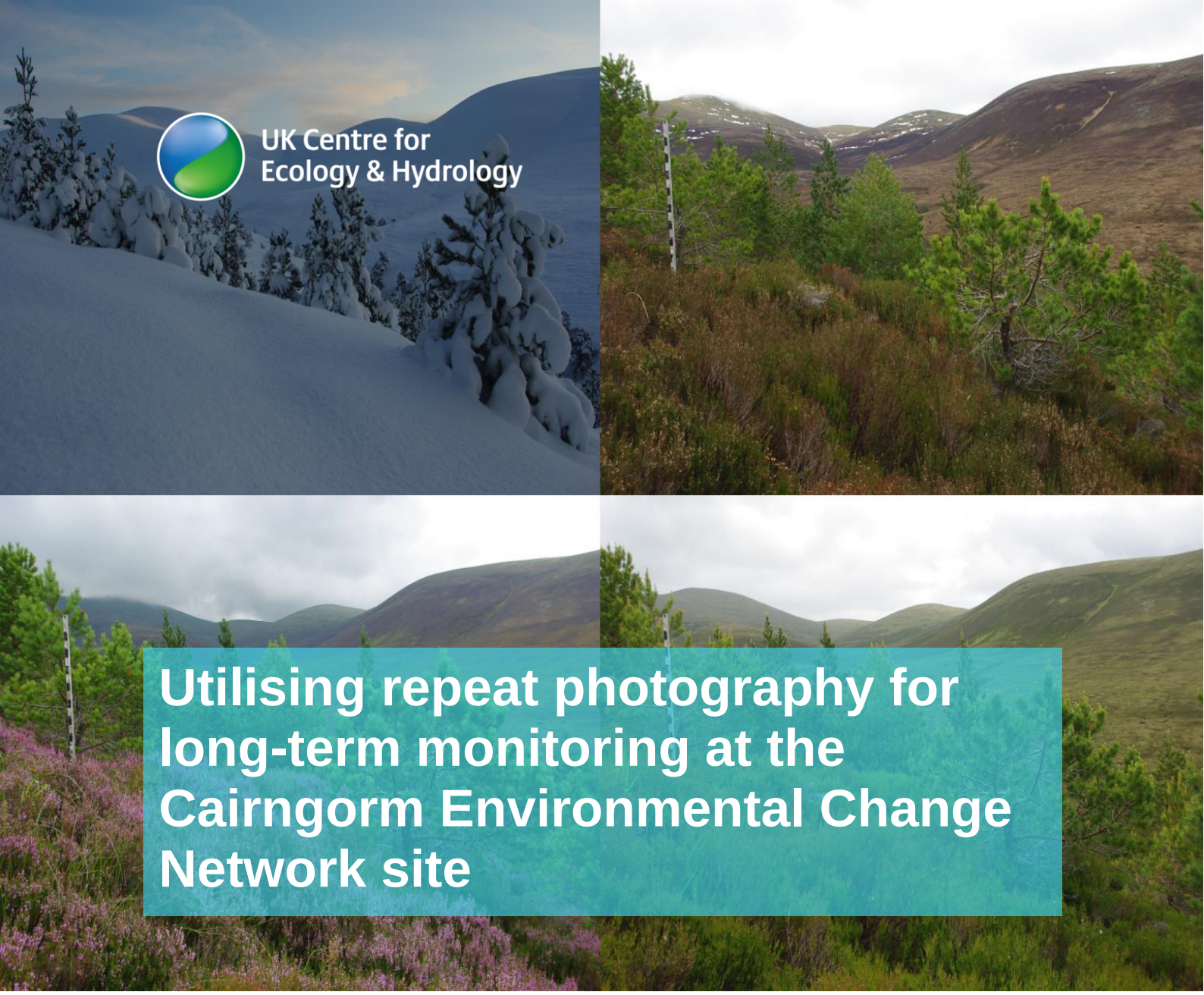

Utilising repeat photography for long-term monitoring at the Cairngorm Environmental Change Network site

Data Analysis Report

Chris Andrews and Jan Dick

Date 28/04/2020

UK Environmental Change Network

UK-SCAPE
UK Status, Change and Projections of the Environment

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Contents

Summary

This report summarises the outcomes from fixed-point repeat photography at the Cairngorms Environmental Change Network research site in the Allt a'Mharcaidh, Scotland. The data covers the timing of multiple snow events as well as invertebrate and plant phenological events (Spittlebug spittlemass, heather flowering, Scots pine tree growth) over either a 17 year period (snow, 2003-2019), or 10 year period (invertebrate and plant, 2010-2019).

Temperature at the site has not significantly changed over the 17 years overall, however two different temperature periods were identified; a general cooling period occurring between 2003 and 2010, followed by a warming phase driven mainly by increased winter temperatures (2010-2019). Duration of snow presence in the catchment was found to have significantly increased over the 17 years, primarily as a result of later spring melt, whilst flushing of pine needles was found to be occurring significantly earlier. Heather flowering and peak spittlemasses did not show any significant temporal response, however all biological phenological events showed strong correlations with May and June mean air temperatures, suggesting they are sensitive to temperature changes in the late spring to early summer and should be continued to be monitored going forward.

A pixel colour counting technique was also tested alongside manual scoring of heather flowering phenophases, and found to be highly complementary. Adoption of the automated pixel colour counting of images is recommended as it removes potential observer error when assigning subjective phenological events to relatively subtle changes in images. However, its use is limited to situations where the region of interest is unlikely to be affected by obscuring weather events.

1 How to use this report

This report starts with a general introduction to phenological research and a background to the Environmental Change Network. A general method chapter covers aspects common to all datasets used in this report, including the Cairngorms monitoring site, camera systems and environmental data. Chapters thereafter focus on detectable phenological events derived from the camera data, including snowmelt, heather flowering, spittlebug spittlemass and Scots pine growth. Each of these chapters includes its own introduction, methods and results/discussion. A final discussion chapter covers the overall findings.

2 Introduction

2.1 Phenological recording

Phenology is “the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” (Lieth, 1974). Common examples given include the timing of budburst in plants, or the arrival of migrant species at a certain location. In a global context, use of phenological monitoring and/or knowledge of phenological events, go back millennia, being essential to both hunter/gathers, farmers and cultural events (Koch et al., 2007). Structured phenological recording in the UK goes back nearly three centuries, with some recording schemes running for over 200 years (e.g. Marsham phenological records from 1736-1947, Sparks & Carey, 1995).

Phenological events are crucial to various aspects of ecosystem function including species fitness and distribution (Chuine, 2010), community assemblage (Gill et al., 1998), and trophic interaction and structures (Edwards & Richardson, 2004). Furthermore, and across multiple scales, many processes such as carbon, water and nutrient cycling are mediated by phenology (Gu et al., 2003, as cited in Richardson et al., 2013).

Many studies have found that spring phenological events have been getting earlier for many species of flora and fauna (e.g. Schwartz & Reiter, 2000; Menzel et al., 2006; Andrews et al., 2011; Menzel et al., 2020), as well as for abiotic events such as snow and ice melt (Andrews et al., 2011). However, changes in the timing of autumn events are less definitive (Menzel et al., 2006; Andrews et al., 2011; Menzel et al., 2020). Several studies have also shown a recent deceleration in the change of spring phenology (Piao et al., 2019; Menzel et al., 2020). Changes in phenological events in upland and mountainous areas are generally even more pronounced than at lower altitudes (Ziello et al., 2009; Menzel et al., 2020), but increased global warming has reduced the effect of elevation on plant phenology, resulting in more uniform springs across elevation (Chen et al., 2018; Vitasse et al., 2018).

Phenology has been recorded in a number of ways. Historically the only available method was through visual on-site observations by recorders, whilst more recently, advancements in remote sensing allow for both fine and wider-scale recording (e.g. Myneni et al., 1997; Menzel, 2000). Fixed-point repeat photography has been

demonstrated to be a useful method for recording phenological change, particularly in remote regions where other methods are difficult to implement. Photography has been successfully used to study a range of biological (e.g. Crimmins & Crimmins, 2008) and environmental (Christiansen, 2001; Hinkler et al., 2002; Bourgault, 2008; Andrews et al., 2011) phenological events. The benefits of extracting phenological data for both biological and environmental events from a single image series is highly desirable in remote areas. Andrews et al. (2011), demonstrated how lake ice melt, snow melt and birch greening could be readily observed from a single weekly image series; providing a suite of observations that demonstrated the impacted of climate change in Northern Sweden.

Here we report on observed changes in the timing of environmental and ecological events recorded on a fixed-point repeat camera at the Environmental Change Network (ECN) site in the Cairngorms National Park, Scotland. This data further increases our knowledge of how ecosystems within the study area are changing in response to a changing climate.

2.2 Environmental Change network (ECN)

The ECN is the UK's long-term, integrated environmental monitoring and research programme. It collects, analyses and interprets a wide range of long-term data from a network of sites across the UK. ECN's current mission is: "To develop and maintain a multi-agency network and early-warning system to detect, present, interpret and predict long-term ecosystem change and help society mitigate and adapt to global change."

ECN summary data can be accessed through the ECN website (http://www.ecn.ac.uk/data), and on request from the ECN Central Coordination Unit. Complete datasets and supporting documentation covering the years 1993 – 2015 are freely available from the NERC Environmental Information Data Centre under the terms of the Open Government Licence (Rennie et al, 2020).

2.3 Aim of this report

This report is one of a series detailing interim analysis of trends in environmental and ecological variables in the ECN Cairngorm long-term monitoring site (Allt a'Mharcaidh catchment). A report on temporal trends in spider communities (Andrews et al., 2020) is available from the NERC open access archive.

This report aims to document and better understand patterns of phenological and environmental change in the catchment, and to identify any potential drivers of change.

3 General methods

3.1 Study area

Long-term monitoring of physical, chemical and biological processes has taken place in the Allt a'Mharcaidh catchment in the Cairngorms National Park (57° 6' 28"N, 3° 50' 6"W) as part of the UK Environmental Change Network (ECN, www.ecn.ac.uk) since 1998. At the heart of the monitoring is a Campbell Scientific automatic weather station (AWS), located at 700 m.a.s.l on the edge of the Cairngorm plateau, from which we derived our environmental data. Further down the slope at 500 m.a.s.l a repeat photography system takes daily photographs for use in monitoring phenological change.

The repeat photography system was targeted toward the north slopes of Sgoran Dubh Mor (1111 m) and north-north-eastern slopes of Meall Bhuidhe (960 m) and Geal Charn (920m), located within in the Allt a'Mharcaidh catchment, which is located in the Invereshie and Inshriach National Nature Reserve, Cairngorms National Park, Scotland. The hillslope visible to the camera covers a range of some 650 meters of altitude, from 450 m.a.s.l in the valley to 1111 m a.s.l at the highest summit. The foreground is a dry heath habitat, and is dominated by heather (*Calluna vulgaris)* and regenerating Scots pine (*Pinus sylvestris) trees* (Fig 1).

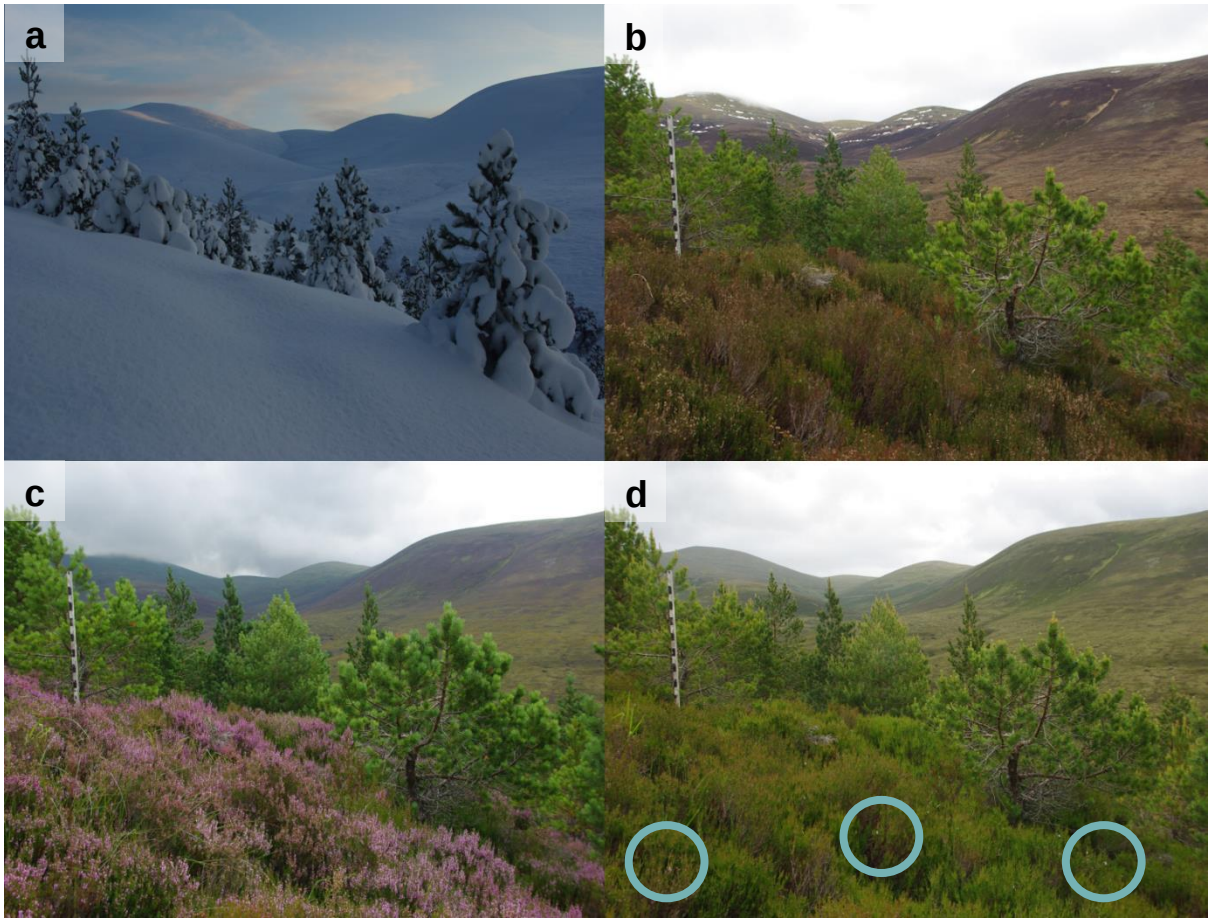

Figure 1 *Example images showing camera view and extractable phenological features including mountain snow (a), snow patches (b), heather blooming (c), Pine (b,c,d) and spittlemass presence (circled) (d).*

3.2 Camera system

Two fixed-point repeat photography camera systems have been used at the site between 13 November 2002 and present. The mark I system operated until 2009, capturing a single daily photograph at midday using an Olympus C860 digital camera, a timer, and a solenoid to actuate the shutter release within a weatherproof housing. From 05 September 2009 the mark II system consisted of a purpose built time-lapse package by Habortronics, utilizing a Pentax K200D DSLR, Pentax 18-55mm zoom lens set at 35mm, and a DigiSnap 2100 Controller contained within waterproof housing fitted with a 5W solar panel for continuous operation. This system records three images daily (0900, 1100 and 1300), increasing the probability of capturing an unobscured image of the hillslope.

3.3 Detectable events

Timing of snow events such as start, end and duration of persistent winter snow presence were readily observable in images from both the mark I and II snow cameras, covering the period from 2003 to 2019 (see example in Fig 1). Due to the reduced image quality of the first generation snow camera, phenological events for *Philaenus spumarius* spittlemass, pine leaf-flush, and heather flowering (see example in Fig 1) have only been recordable from 2010 onwards, after the new (mark II) camera system was installed.

3.4 Environmental data

Hourly air temperature (°C) was recorded at the ECN weather station located at 700m.a.s.l within the catchment. As a consequence of sporadic problems in the measurement of precipitation at the ECN AWS, additional data for precipitation and temperature have been obtained from the Met Office weather station at Aviemore, approximately 10km North of the sampling area (Met Office, 2012). To deal with occasional missing air temperature data, a modelled dataset was created using linear regression between ECN and Met Office hourly data. The two temperature datasets were highly correlated (r^2= 0.92, p= <0.001).

Prior to analysis, data were summarised as monthly means for temperature and monthly totals for precipitation. Due to strong seasonal variations in temperature masking year-to-year variation, the data was de-seasonalised using STL decomposition (Seasonal Decomposition Of Time Series By Loess; Cleveland et al, 1990) in R (R Core Team, 2018). STL decomposition works by generating three datasets from the raw temperature data.

1. A seasonal component – the mean temperature for each month across all years.
2. A time-series trend – loess-smoothed trend of seasonally adjusted data (the raw data minus the seasonal component).
3. The remainder/noise – raw data minus the seasonal and trend components.

The trend and remainder values were then added together to create the de-seasonalised temperature dataset for use in further analyses.

Monthly North Atlantic Oscillation (NAO) data, which has been shown to be strongly correlated with winter snow cover in Scotland (Spencer & Essary, 2016), was extracted from the Climatic Research Unit, University of East Anglia, database (Jones et al., 1997).

4 Data analysis

4.1 Climate and environmental change 2003-2019

As photographic data runs from 2002-2019 for snow, from 2010-2019 for phenology, the climate data has also been considered within these two different periods.

Between 1 January 2003 and 31 December 2019 the climate at the site has shown large annual variations but no significant overall temporal trend (Fig 2). However, the seasonally de-trended mean temperature appeared to show some decline between 2003 and 2010, before partially recovering from 2010-2019.

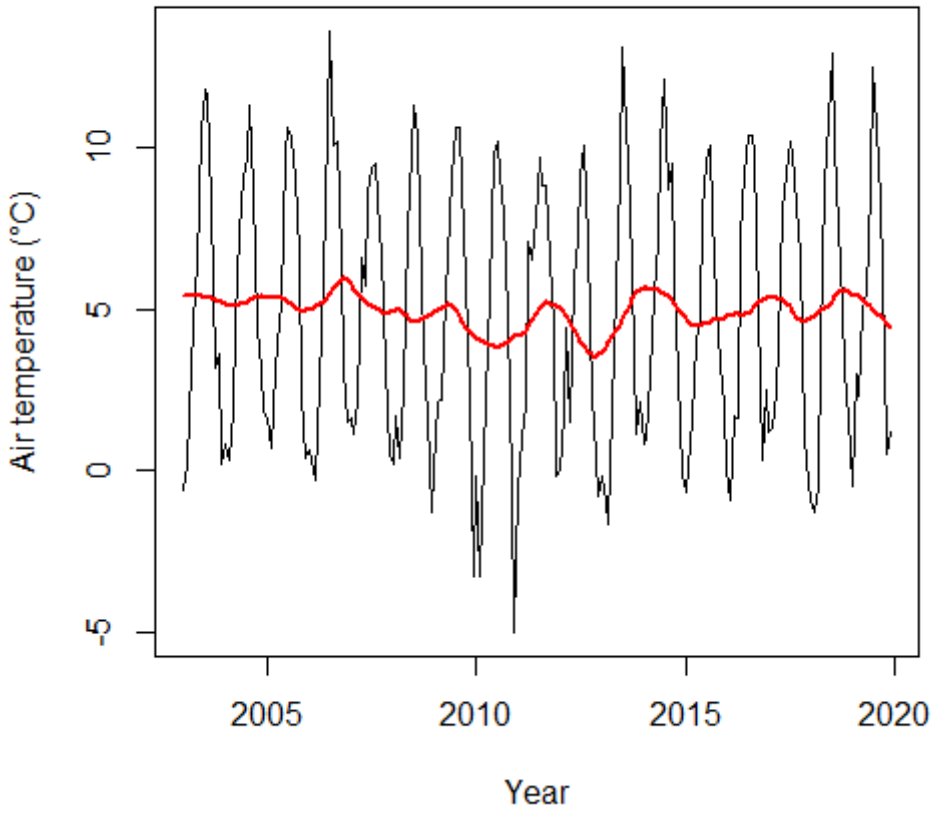

Figure 2 *Mean monthly temperature (°C) between 2003 and 2019 at 700 m.a.s.l. with seasonal and trend decomposition using Loess (red line). Allt a'Mharcaidh catchment, Cairngorms NP, Scotland.*

For the latter period (2010-2019), which covers the period of phenological monitoring, regression analysis shows that air temperature has increased significantly ($F(1,118)= 45.916$, $p= <0.001$). This appears largely driven by significant increases in the mean winter temperature ($F(1,8)= 6.065$, $p= 0.039$) (Fig 3).

Some caution is required however, to prevent over interpretation of the temperature trends. As the dataset is of short duration, the exceptionally cold winter of 2010 exerts a large degree of influence on the overall trends.

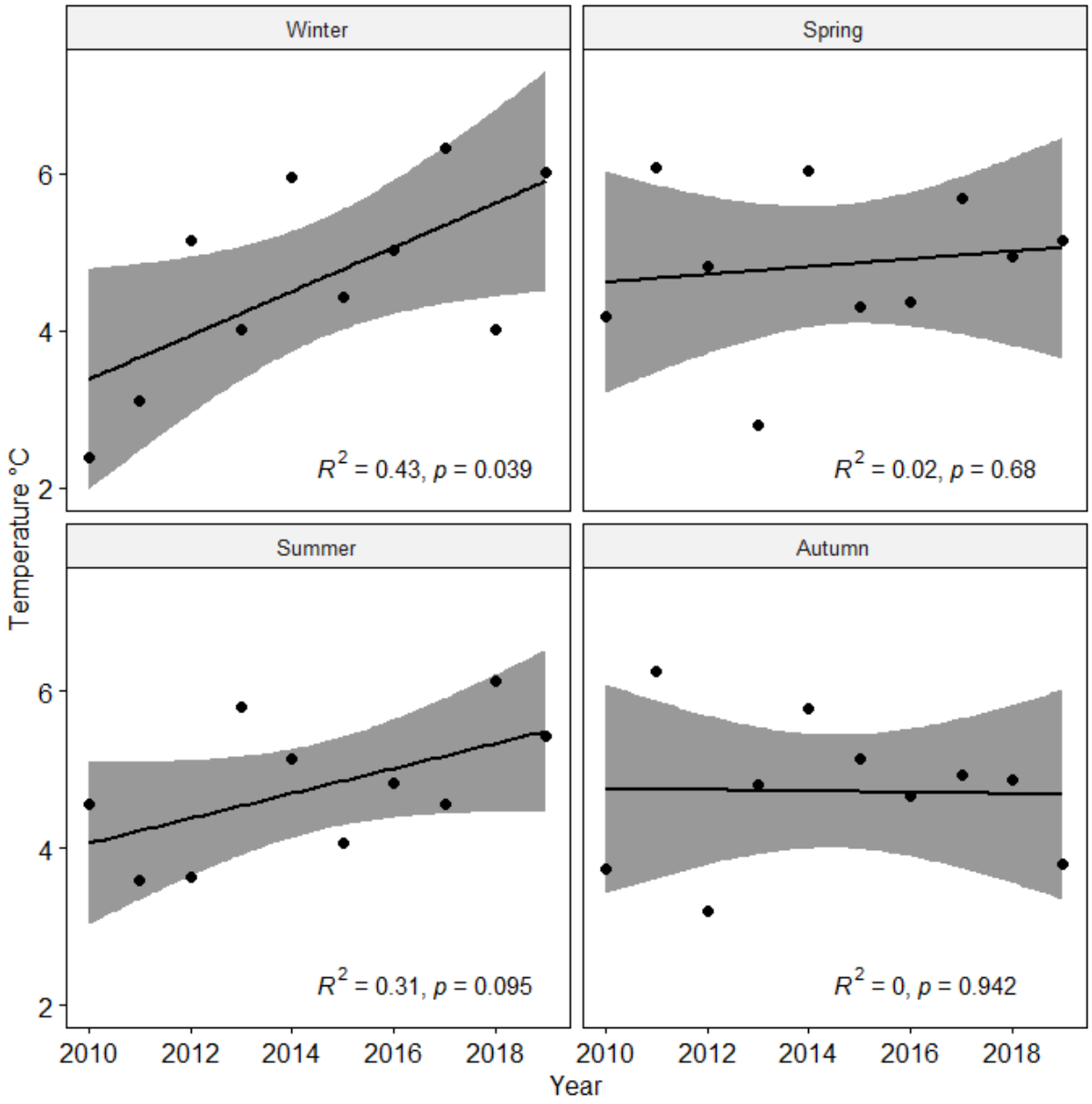

Figure 3 *Temporal patterns for de-seasonalised seasonal mean temperatures between 2010 and 2019. Temperature was de-seasonalised using STL decomposition prior to analysis. Linear regression and 95% confidence limit shown.*

Between 2003 and 2019 the mean annual precipitation at the site was 930 mm, ranging from a minimum of 629 mm to a maximum of 1149 mm. Precipitation appeared to show no temporal trend over the 17 year period, or for the shorter period from 2010 to 2019.

4.2 Timing of snow presence and duration

4.2.1 Rationale

The presence, depth and duration of snow cover in mountain regions has a number of ecological and socio-ecological implications. At the fine-scale snow can protect individual plants from extreme temperatures, desiccating winds or grazing pressure during winter. More widely snow can impact the length of available growing season, or provide benefits in terms of winter snow sports and tourism. The huge quantities of water locked up as snow at higher elevations can also pose a considerable flooding risk in times of rapid thaw, but also helps to regulate water flow throughout the spring and early summer.

Studies by Harrison et al. (2000), Trivedi et al. (2007) and Brown (2019) have all predicted decreased snow cover in Scotland in a future warming scenario, whilst Rivington et al. (2019) show the same for the Cairngorm region specifically. Contrastingly Andrews et al. (2016) provided some evidence for localised variations in current trends, which may be accounted for by either local micro-climates (Brown, 2019), or else be potentially anomalous due to the short time series (Brown, 2020). Indeed, since the suspension of the Snow Survey of Great Britain (SSGB) in 2007, other methods are required to monitor changes in winter mountain snow-cover. Satellite imagery is likely to be more extensively used going forward, but problems remain around the frequency of useable images. At specific locations satellite passes may lack the required frequency, whilst cloud cover on and above the upper slopes of mountains, minimise the number of days where useful images may be obtained.

4.2.2 Methods

The day of year was recorded for the first date of persistent snow (i.e. snow that does not then melt until the spring), and the last day with any visible laying snow in the subsequent spring. Snow duration is the number of days between these two dates. Where data were missed on the automatic repeat photography system due to obscuring weather or a system failure, secondary manual photographs taken during weekly site visits were used to provide bridging data of snow conditions. Where melt day occurred between two weekly images, the day of melt was subjectively estimated based on size of remnant patches in the final image containing snow; and would carry an error of ±3-4 days. In 2005 complete snow melt occurred on day 127, but was followed by another snowfall on day 130, which then persisted for a further 22 days. Here we used the earliest melt date as this represents the end of persistent winter snow cover.

4.2.3 Results

For the 17 winters between 2002/03 and 2018/19 the duration of snow present in the Allt a'Mharcaidh catchment varied each winter by up to 118 days, ranging from 142-260 days (Table 1).

Table 1 *Metadata for the timing of snow formation (first day of persistent winter snow cover), snow melt (last day with any remnant snow patches) and snow duration (number of days between snow formation and melt), in the Allt a'Mharcaidh catchment for winters between 2002/03 and 2018/19.*

Event	Years recorded (no. years)	Median event day	Day of year min/max (range - days)
Snow formation	2002-18 (17)	314	282-350 (68)
Snow melt	2003-19 (17)	156	116-184 (68)
Snow duration	2003-19 (17)	208	142-260 (118)

The data is skewed by the exceptionally long snow presence recorded in the winters of 2012/13 and 2013/14 (260 and 255 days of snow presence respectively), where snow persisted for more than 50 days longer than the predicted duration of 204.1 and 207.5 days respectively (based on regression slope: y= -6599.85 + 3.38x. Fig 4a). Over the 17 years the period of snow presence was found to have increased significantly ($F(1,15)= 6.712$, $p= 0.02$) by 3.4 days per year (57.5 days total) (Fig 4a).

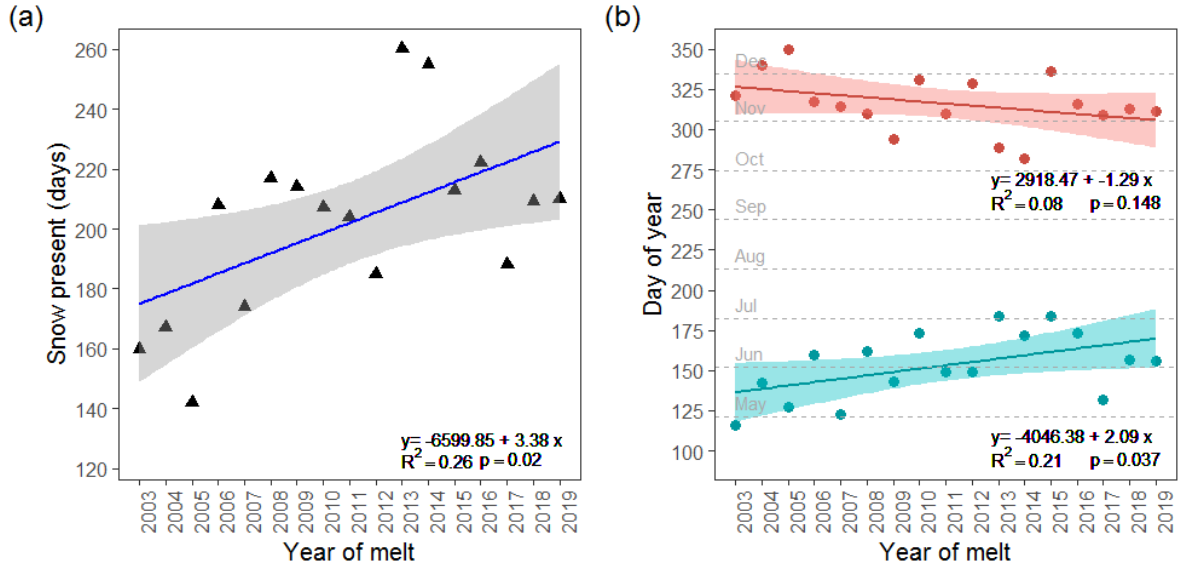

Figure 4 *Winter snow presence in the Allt a'Mharcaidh catchment, Cairngorms NP, for 17 winters between 2003 and 2019. (a) The number of days of persistent winter snow presence and (b) Start date (red) and end date (green) of persistent winter snow cover. Linear regression lines and 95% confidence limits shown. First day of each month represented by grey dashed line.*

Although both the onset of winter snow and subsequent spring melt both appeared to be changing (getting earlier and later respectively, Fig 4b), only the change in spring melt was significant over time ($F(1,15)= 5.235$, $p= 0.037$), getting later by 2.1 days per year over the 17 years (35 days in total).

Although no significant changes were observed in the late winter-spring mean temperature (January-June) over the 17 years, the date of complete spring snow melt was found to correlate significantly with changes in mean seasonal temperature ($F(1,15)= 16.57$, $p= 0.001$, $r^2= 0.52$) (fig 5).

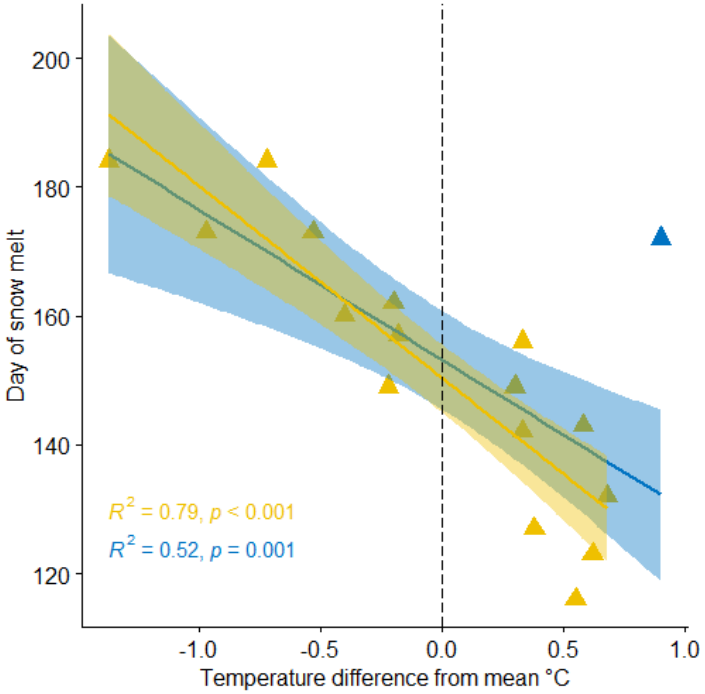

Figure 5 *Relationship between de-seasonalised winter-spring (January-June) temperature and the last day of persistent snow presence in the Allt a'Mharcaidh catchment, for 17 winters between 2002/03 and 2018/19. Temperature is displayed as the difference from 2003-2019 mean. Regression line and 95% confidence limit shown. Yellow removes the outlying exceptional winter of 2013/14 (blue triangle – see text).*

This evidence suggests snow duration at the site is sensitive to modest changes in seasonal temperatures, and we could expect any future winter-spring warming under climate change to have substantial effects on the duration that snow is persistently present in the catchment. A major outlier occurred during the winter of 2013/14, where warmer temperatures resulted in later than expected snow melt (Figure 5). Winter 2013/14 was characterised across the region by exceptionally large accumulations of snow above 600m from December through to March (Cameron et al., 2015). Larger accumulations, as witnessed in 2013/14, are likely to be less sensitive to climatic conditions (Trivedi et al., 2007), and despite a warmer than usual spring, the large depth of snow required to melt resulted in a much later melt date than was predicted by the model. As the regression model does not fit well for extreme events as occurred in 2013/14, dropping the outlier from the regression analysis has the effect of strengthening the relationship between temperature and day of melt ($r^2= 0.79$), with 1°C of warming resulting in snow melting around 29 days earlier ($F(1,14)= 54.08$, $p= <0.001$).

Temperature is well known to be the primary factor influencing snow cover (e.g. Beniston, 2003; Trivaldi et al., 2007), and further analysis here showed no relationship between snow melt and other winter-spring climatic drivers (precipitation, air pressure). Snow duration showed a weak but significant association with air pressure $r= -0.52$, $p= 0.032$), although this did not correlate with timing of snow formation or melt. In contrast to other studies in the UK, where a clear link between snow cover and the winter NAO has been shown (Spencer & Essery, 2016; Brown, 2019), no such relationship was obvious in our data. However, it is possible that this relationship does not extend easily to localised late laying snow patches, which exist mainly on the

steeper leeward north-to-northeast facing slopes and crags, where snow can accumulate and receive little direct sunlight for much of the winter-spring period.

Although the sensitivity to winter-spring temperatures is a clear effect, it is important to note that the 17 years of data reported here is a relatively short period for looking at climatic changes. The temporal increase is snow presence duration is somewhat compromised by the start years where snow duration was particularly short, followed by some exceptional snow years in the latter period (particularly the winters of 2012/13 and 13/14). The SSGB ran in one form or another from 1945-2007, collecting subjective data on snow cover in altitudinal bands within a particular field of view (Spencer et al., 2014). Research looking at long-term trends in this data, and forecast modelling under different climate scenarios, have shown that snow cover duration has decreased in Scotland over the period and is predicted to do so into the future (Trivedi et al., 2007; Brown, 2019; Rivington et al., 2019).

4.3 Heather flowering phenology

4.3.1 Rationale

Upland heather moorland has considerable economic, nature conservation, landscape, aesthetic and tourism-related value (Thompson et al., 1995). Because of intensive land management, the UK now includes extensive areas of open heather moorland, and it is therefore an internationally important landscape.

Although the flora of heather moorland is relatively poor (Ratcliffe & Thompson, 1988), it supports a huge diversity of animal assemblages, including particularly for Tipulids (Craneflies), ground dwelling invertebrates (Usher & Thompson, 1993) and pollinating invertebrates such as the Lepidoptera (Coulson et al., 1988). In turn, the rich diversity of invertebrates supports a diverse bird fauna.

Changes in the timing of heather flowering therefore has the potential to affect the ecosystem through phenophase mismatching between plant and pollinators (e.g. Wall et al., 2003; Memmott et al., 2007), resulting in a reduced food resource for insects, or a lack of available pollinators for plants.

4.3.2 Methods

Heather flowering phenology was scored both using manual assessment of photographs and through a pixel counting technique. The latter was undertaken due to the large degree of subjectivity involved in pinpointing flowering onset, peak and end from photographs. In the manual assessment, onset was considered to have occurred when the flowers on more than one plant appeared fully developed in part of the image. The peak was the first date when flowering appeared most extensive, and the end of flowering when all flowering appeared to have finished/flowers faded.

Prior to analysis using the pixel count method, the foreground area of each photograph was cropped out to 1200x500 pixels starting from the bottom left corner of each image, and converted to 256 colours using Irfanview batching processing software. Coloured pixels in the RGB triplet range [0.7, 0.1, 0.7] ±30% (roughly pink/purple) were identified using CountColors package in R (Weller, 2019), and the proportion of coloured pixels relative to the background pixels was returned for further analysis.

During both the early season when there were few flowers present, and the post flowering period when spent flowers remained on the plants, certain light and weather combinations occasionally resulted in false positives in the colour count method (i.e. counting designated colours that were not actually present). To minimise this effect flowering was considered to have begun/ended when the pixel count on a given day was at least 20% of the maximum count for that year. A flowering curve was generated for each year by fitting a general additive model (GAM) to the constrained dataset (e.g. fig 6). As with previous studies such as by Jentsch et al. (2009) and Nagy et al. (2013), the mid-flowering date was calculated as the 50th percentile of the flowering curve over the entire flowering period. The length of peak flowering was calculated as the difference in days between the 25th and 75th percentile (fig 6). A full range of flowering curves is available in the supplementary material (S2).

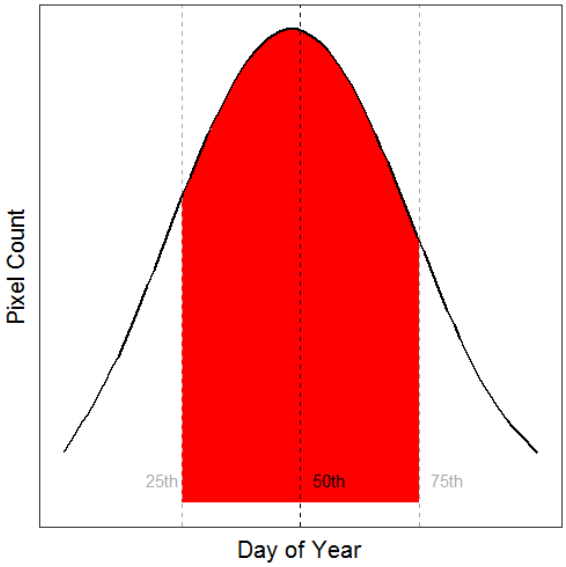

Figure 6 *Example image of GAM generated flowering curve using pixel count of a determined colour range. Peak flowering period is highlighted in red and is calculated as the difference between 25th and 75th percentiles of flowering curve. The mid-flowering point (50th percentile) is also shown.*

4.3.3 Results

Differences between the two methods of recording heather flowering were checked using ANOVA for both the onset of flowering, and the onset of peak flowering. No significant difference was found between the manual and colour counting methods in both instances (onset: $F(1,18)= 0.193$, $p= 0.666$; peak onset: $F(1,18)= 0.134$, $p= 0.718$, Fig 7). As such, we selected the colour counting output for the rest of the analysis as it offers a more robust approach to assigning phenological event.

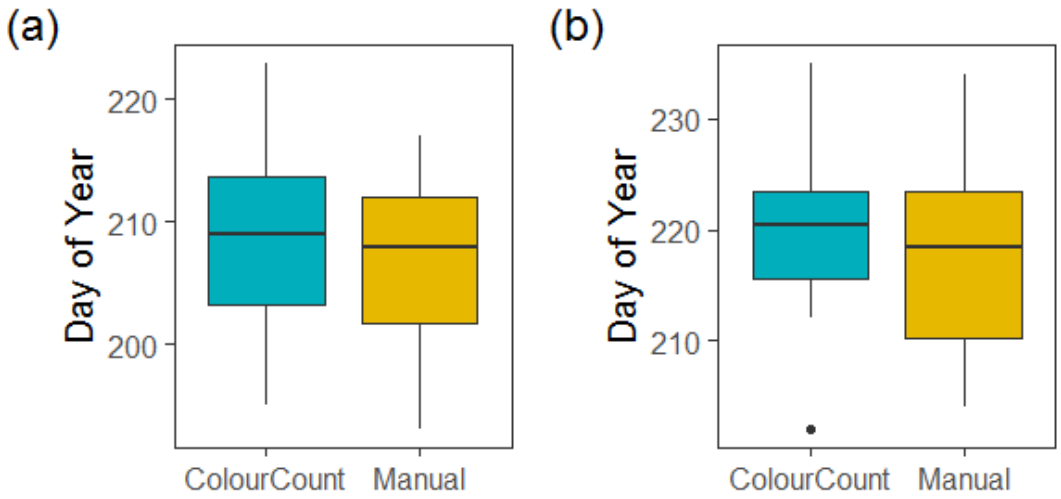

Figure 7 *Yearly onset of flowering (a) and onset of peak flowering (b) for Calluna vulgaris between 2010 and 2019; established by analysing daily landscape photographs using two different methods: counting of defined range of coloured pixels (ColourCount) and human assessment (manual).*

There were no apparent temporal trends for flowering onset, mid-flowering date or peak flowering duration (Fig 9). Onset of flowering ranged between days 195 and 223 (Table 2), and correlated most strongly with the mean May air temperature ($R= -0.83$, $p= 0.003$; Fig 8), and slightly less so with the late-spring early-summer mean

temperature (May-July: R= -0.80, p= 0.005). For every 1°C rise in mean May temperature, onset advanced by 5.4 days (F(1,8)= 17.58, p= 0.005). A full range of temperature and precipitation correlations for heather flowering is available in the supplementary material (S1). These results are comparable to other studies looking at the effects of May temperature on flowering onset. Nagy et al. (2013) for example found onset of *C. vulgaris* in central Europe advanced by 6.5 days for every 1°C rise in May temperature.

Table 2 *Phenological metadata for heather (Calluna vulgaris) flowering in the Allt a'Mharcaidh catchment between 2010 and 2019. Events marked with * are number of days, all others are day of year. Two methods of data collection were utilised; human assessment (manual), and colour pixel counting using r package ColorCount (colour count).*

Event	Method	Years recorded (no. years)	Mean event day ± s.e.	Day of year min/max (range - days)
Flowering onset	Colour count	2010-19 (10)	208 ± 2.8	195-223 (28)
	Manual	2010-19 (10)	206± 2.5	193-217 (24)
Peak flowering onset	Colour count	2010-19 (10)	219 ± 2.8	202-235 (33)
	Manual	2010-19 (10)	218 ± 3.0	204-234 (30)
Mid flowering day	Colour count	2010-19 (10)	232 ± 2.9	214-247 (33)
Peak flowering period*	Colour count	2010-19 (10)	27.5 ± 2.2	18-41 (23)

Mid flowering day ranged between day 210 and 247 (30 Jul-05 Sept) (Table 2), and was very strongly correlated with the mean May-July temperature (R= -0.94, p= <0.001), as well as all months throughout the late-spring early-summer period (table S1). The mid-flowering date was found to advance by 8.96 days for every 1°C rise in mean May-July temperature (F(1,8)= 58.09, p= <0.001).

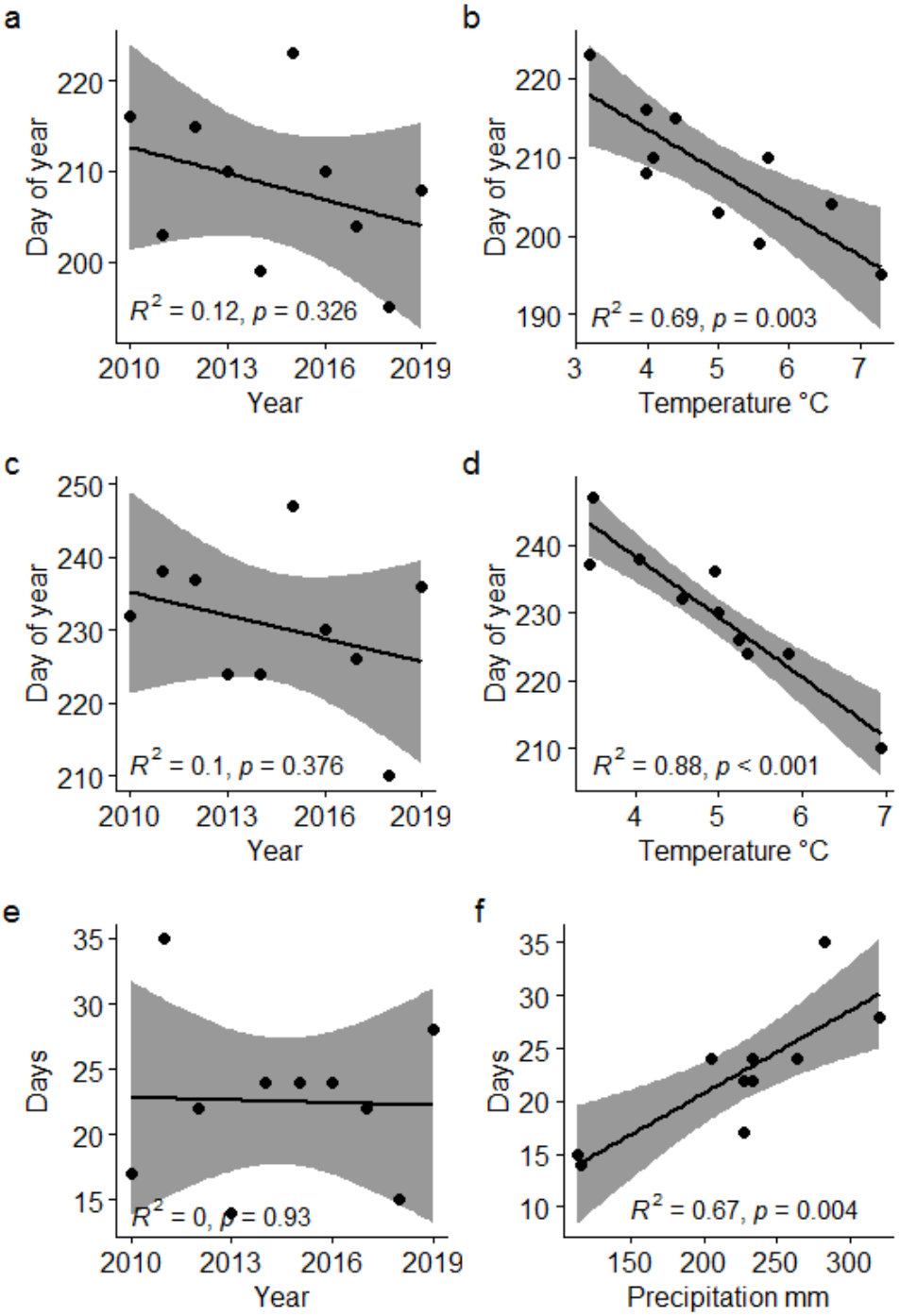

Figure 8 *Effect of time (a,c,e) and environmental variable with highest correlation (b,d,f) on Calluna vulgaris flowering onset (a,b), mid-flowering date (c,d) and peak flowering duration (e,f) between 2010-2019. Flowering onset correlated strongest with mean May temperature (b), mid-flowering date with mean May-July temperature (d), and duration with total June-August precipitation (f). Regression lines with 95% confidence limits shown. Temperature was de-seasonalised using STL decomposition.*

The duration of peak flowering season showed no response to temperature, but was significantly correlated with total August precipitation (R= 0.63, p= 0.049), and total summer precipitation (June-August; R= 0.82, p= 0.004), both of which included at least part of the flowering season (July and/or August). The duration of peak flowering season was further found to extend by 7 days for every 100mm of rain during the summer months ($F(1,8)= 16.37$, p= 0.004). This contrasts with Nagy et al. (2013) who found increased heavy rainfall events resulted in a shortened flowering duration for *C. vulgaris*. The mid-flowering date also showed some correlation with precipitation, particularly for July; however, a degree of caution is required in the interpretation as July precipitation was also strongly correlated with summer monthly and seasonal air temperatures (supplementary material S1).

4.4 Spittlebug phenology

4.4.1 Rationale

Interest in xylem feeding insects such as the spittlebug *Philaenus spumarius* has increased recently due to its potential to spread the bacterium *Xylella fastidiosa,* a pathogen of some broadleaf tree species, recently responsible for extensive dieback of olive trees in Italy.

Spittlebugs, although species poor, are one of the most important phytophagous insects in meadow and moorland habitats in Northern Britain (e.g. Eyre et al, 2001; Eyre, 2005). Spittlebugs in the UK generally produce one generation per year, with the five nymphal stages living within a self-produced spittlemass (often referred to as Cuckoo-spit in the UK) as a way of regulating temperatures and for predator avoidance (Whittaker, 1970, Tonelli et al., 2018). As numerous nymphs frequently aggregate into the same spittle on a host plant, spittlemass in themselves do not necessarily provide a good measure of population density. This can be corrected through the recording of nymphs per spittle, as has taken place in the wider Allt a'Mharcaidh catchment as part of routine ECN monitoring (http://www.ecn.ac.uk/measurements/terrestrial/i/is).

Philaenus spumarius is widely distributed throughout the Palearctic regions (Cornara et al., 2018), and is well represented in northern Britain. Both the adult and nymph are xylem feeders, preferentially targeting the new growing stems of the plant. It is one of, if not the most, polyphagous insects currently known (Ossiannilsson, 1981), which helps explain its wide distribution throughout Europe and across numerous habitat types (Halkka & Halkka, 1990; Stewart & Lees, 1996).

Numerous studies over many years have tried to correlate *P. spumarius* development with temperature (typically using heat-sum), but no clear and consistent data on the influence of temperature has yet been established (Cornara et al., 2018).

4.4.2 Methods

The nymphs of spittlebugs, considered here to be *P. spumarius* due to location, occurrence on *C. vulgaris* (heather), and previous sampling in the catchment, produce spittlemasses which readily observable in the foreground of photographs during the early summer. These spittlemasses can be both counted and the onset and end of occurrence date stamped.

To avoid the risk of incorrect determination, and/or the influence of a single spittlebug nymph not representative of the wider cohort, the date of first spittlemass appearance was considered reached when two spittlemasses could be seen in a single image. Further data was collected for the date of peak spittlemass occurrence (the date with highest count of observable spittlemasses). Spittlemass duration is the time (days) between first and last observable spittlemass.

For analysis with temperature, we use monthly mean temperature as no consistent base temperature has been established for heat-sum models (see Cornara et al., 2018 for an overview).

4.4.3 Results

The first appearance of *Philaenus spumarius* spittlemasses were recorded from the last day of May to the end of June (Table 3), with peak spittlemass occurring approximately 17 days after the first. The last visible spittlemass generally occurred 16 days after the peak, around mid-July, giving an average spittlemass presence of 32.6 days per year.

Table 3 *Phenological metadata for Philaenus spumarius spittlemass recorded in the Allt a'Mharcaidh catchment between 2010 and 2019. Events marked with * are number of days, ** spittlemass counts, whilst all others are day of year.*

Event	Years recorded (no. years)	Mean event day ± s.e.	Day of year min/max (range - days)
First spittlemass	2010-19 (10)	162 ± 2.8	149-180 (31)
Peak spittlemass	2010-19 (10)	179 ± 3.4	164-196 (32)
Last spittlemass	2010-19 (10)	195 ± 3.4	177-212 (35)
Spittlemass duration*	2010-19 (10)	32.6 ± 2.1	23-40 (17)
Peak count**	2010-19 (10)	24.6 ± 4.7	13-63 (50)

No temporal trends were found for any of the phenological event dates, duration of presence or peak spittlemass count (Table 4).

Table 4 *Pearson's correlation coefficients (r) for three phenological stages of Philaenus spumarius spittlemass presence, the total duration spittlemass were present and peak spittlemass count, and potential environmental drivers for 10 years (2010-2019) in the Allt a'Mharcaidh catchment.*

		Year	Onset	Peak	Last	Duration	Peak count
Date of onset		-0.09	-				
Date of peak spittlemass		-0.21	0.90***	-			
Date of last spittlemass		-0.22	0.77**	0.88***	-		
Spittlemass duration		-0.22	-0.09	0.22	0.56	-	
Number of spittlemass at peak		-0.14	-0.64*	-0.52	-0.22	0.49	-
Mean temperature:	Jan	0.01	-0.33	-0.46	-0.36	-0.14	0.31
	Feb	0.38	0.04	0.06	-0.07	-0.17	-0.15
	Mar	-0.03	-0.04	-0.08	-0.06	-0.04	-0.01
	Apr	-0.03	-0.36	-0.18	-0.01	0.46	0.39
	May	0.42	-0.76*	-0.79**	-0.85**	-0.34	0.17
	Jun	0.33	-0.66*	-0.67*	-0.44	0.16	0.59
	Mar-Apr	-0.04	-0.27	-0.18	-0.05	0.28	0.26
	Apr-May	0.21	-0.72*	-0.59	-0.49	0.17	0.41
	May-Jun	0.42	-0.80**	-0.82**	-0.74*	-0.12	0.41
	Jun-Jul	0.44	-0.54	-0.48	-0.36	0.15	0.52
	Mar-May	0.15	-0.57	-0.5	-0.41	0.1	0.31
	Apr-Jun	0.3	-0.82**	-0.72*	-0.56	0.19	0.55
Total precipitation:	Jan	0.23	0.56	0.48	0.27	-0.31	-0.41
	Feb	0.33	-0.07	0.11	0.04	0.16	0.04
	Mar	0.48	0.21	0.28	0.43	0.4	-0.09
	Apr	-0.03	0.45	0.23	0.03	-0.55	-0.45
	May	0.16	0.4	0.49	0.44	0.16	-0.31
	Jun	0.35	-0.1	-0.05	-0.01	0.12	-0.12
	Mar-Apr	0.39	0.52	0.42	0.39	-0.08	-0.42
	Apr-May	0.08	0.54	0.46	0.3	-0.24	-0.48
	May-Jun	0.3	0.24	0.34	0.32	0.18	-0.29
	Jun-Jul	-0.2	0.01	0.15	0.37	0.58	0.16
	Mar-May	0.3	0.5	0.48	0.43	0.03	-0.4
	Apr-Jun	0.21	0.43	0.38	0.26	-0.16	-0.47

* p= < 0.05; ** p= < 0.01; *** p= < 0.001

Mean May temperature appeared to be the key month with regard to onset, peak and last date of spittlemass presence (Fig 9), whilst June also correlated, to a lesser

degree, for date of onset and peak, but not for the end date. Onset was found to occur 5.2 days earlier for every 1°C rise in mean May temperature (F(1/8)= 11.08, p= 0.01; fig 9a). It has also been previously shown that milder winters can result in earlier egg hatching (Masters et al., 1998), and therefore an earlier onset of spittlemass. However, no such relationship between winter temperatures and onset was visible in our data (table 4).

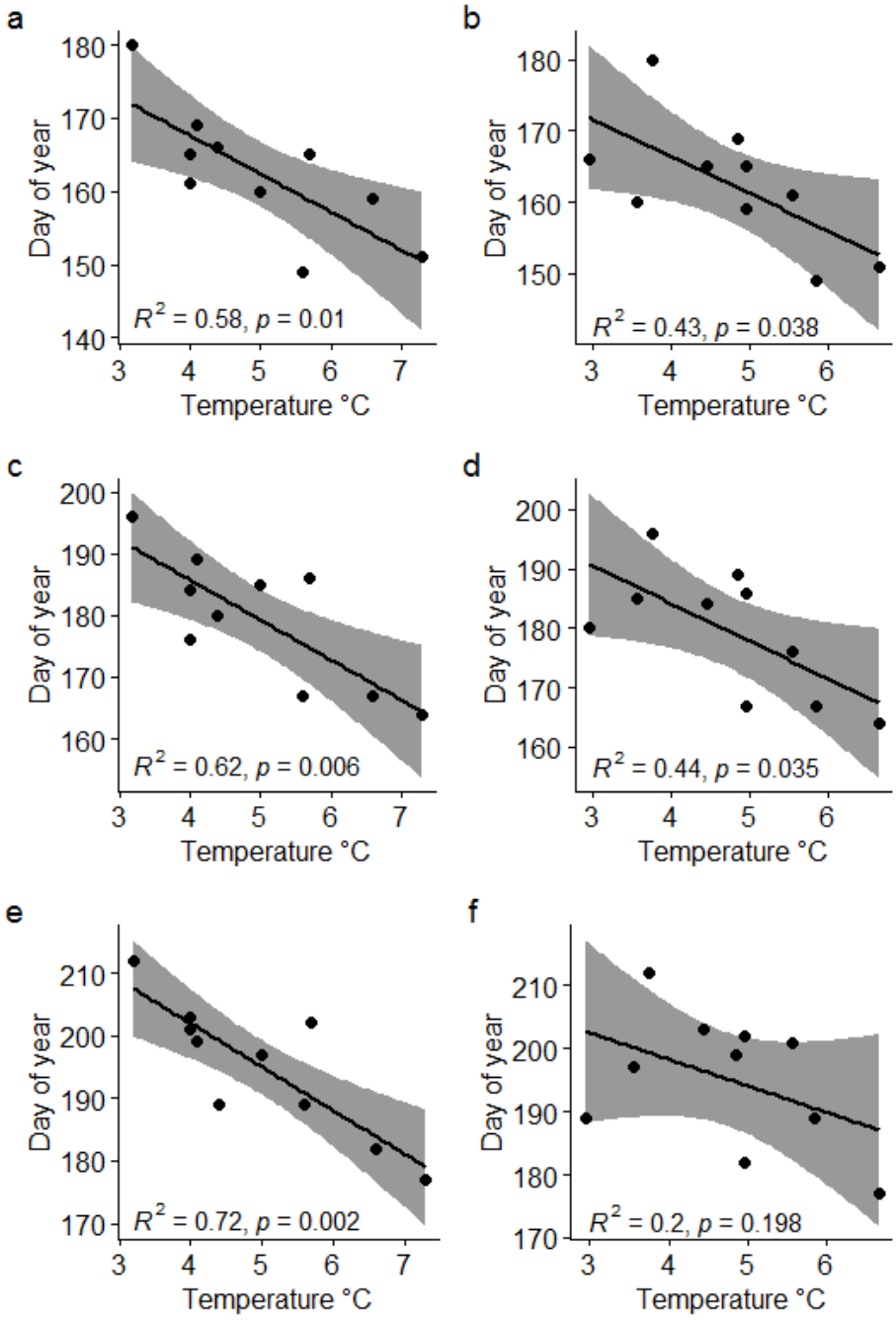

Figure 9 *Date of onset (a,b), peak (c,d) and last (e,f) Philaenus spumarius spittlemass as recorded on a remote camera, with May (a,c,e) and June (b,d,f) mean temperature (deseasonilsed), in the Allt a'Mharcaidh catchment (2010 – 2019). Regression lines and 95% confidence limits shown.*

Duration of spittlemass presence was approximately 33 days (table 4), and was not found to correlate with temperature, precipitation or any other phenological events (table 5). It is possible this is because the recorded duration covers the presence range of all spittlemasses in that year, whilst any individual spittlemass may exist for shorter time-periods. It should be noted, however, that the five pre-imaginal stages that produce a spittlemass, are generally considered to take 35-42 days to develop through to adult spittlebugs, a not to dissimilar time to our recorded duration period. Weaver and King (1954 – in Cornara et al., 2018), recorded that colder weather can greatly extend this pre-imaginal period from 35 to 100 days. However, no evidence for extended duration in colder weather was obvious from our data.

An apparent correlation between onset and peak spittlemass count should be treated with extreme caution. It is driven largely by the spittlemass count in 2014, which was nearly double the next highest count (63 in 2014 compared to 34 in 2010), and 2.6 times the pooled mean. The potential reasons for the exceptionally high spittlemass count in 2014 is yet to be established.

As the available data is limited to a small patch of dry heath in front of a single camera, it is not possible to extrapolate how spittlebugs might have responded over a wider area. Theoretically, at least, locally derived temperature lapse rates could be used to estimate how spittlemass events might vary with altitude close to the recording site. The summer lapse rate in the Allt a'Mharcaidh is 0.64(±0.06)°C per 100m. Comparable habitat situated on a similar aspect to that of the camera is found, to varying degrees of extent, between 325-625 m.a.s.l. Using the regression equation ($y = -5.219\text{x} + 188.489$) (fig 9a) for the effect of mean May temperature (x) on spittlemass onset (y), the date of onset could vary by approximately 10 days between the upper and lower altitudinal limits. However, ground truthing would be required to test the accuracy of such predictions, as other factors such as exposure to extremes of wind and temperature likely to become increasingly important as altitude increases.

4.5 Pine leaf-flush phenology

4.5.1 Rationale

Spring growth of *Pinus sylvestris* L. follows a typical phenological cycle to many pine species in northern temperate regions (Dougherty et al., 1994). The cycle involves setting buds and growth cessation toward the end of the growing season, followed by entering dormancy, cold hardening, dormancy release, and bud break in the spring (assuming chilling requirements have been met). In temperate regions, bud-break is primarily determined by the degree of winter chilling, photoperiod and temperature (e.g. Chuine & Cour, 1999). This combination of factors helps protect the tree from potential frost damage due to early bud burst. However, for *P. sylvestris* the promotive effect of long photoperiods on the timing bud burst is greatly reduced following a relatively short chilling period (c. 40 days at 4 °C), and therefore likely has little effect from March onwards in northern temperate regions (in Cannell & Smith, 1983).

Although increasing temperatures will likely result in phenophases such as bud burst occurring earlier in the year, and thus expose trees to potential sub-zero cold snaps, it is unlikely to prove catastrophic for *P. sylvestris* in Scotland. Frost hardiness of *P. sylvestris* varies throughout the year, but even in summer when needles are most frost sensitive, they can withstand temperatures of -10 °C (Beck et al. 1995). Although such temperatures can occur each winter, it is extremely unlikely outside of the winter season. In the previous two decades (available data), such cold temperatures have never occurred at the Aviemore Met Office weather station outside of November-March winter period.

Here the monitoring of pine phenology acts as another measure of phenological change within the landscape, and no attempt is made to understand the potential underlying mechanisms of phenological change.

4.5.2 Methods

Although new annual growth of *P. sylvestris* was clearly visible in photographs, it was difficult to identify a robustly identifiable fixed point in the growth cycle on a year-to-year basis. This was in part due to the camera being setup to focus on distant mountain snow, resulting in a soft focus of the foreground in some photographs. The growth point considered as being most robustly identifiable was the flushing of new needles away from the new growth stem (sometimes referred to as a ‘candle’ – Fig 10). Unlike previous studies observing budburst alone, the leaf flush date is a product of the date of budburst and subsequent growth rate, and therefore may not be reliably comparable to studies focusing on budburst.

Figure 10 *Examples images for the 'Candle' phase of new growth on Pinus sylvestris (Left) and post needle flush (Right). Cairngorms, Scotland. The date of observable needle flush was recorded as a phenological event.*

Prior to the seasonal de-trending of temperature data (see general methods, 2.4), growth degree-days were calculated using daily mean temperatures. We used a temperature threshold of 5°C, following other studies that have adopted a Growing Degree Days (GDD) approach with *P. sylvestris* (e.g. Seo et al., 2008; Swidrak et al., 2011). Following Cannell & Smith (1983), heat sum was calculated from 01st February to the phenological event date, whilst chill-days, the number of days <5°C, were calculated from 01st November to date of leaf flush date.

4.5.3 Results

Mean leaf flush date occurred on day 178 (± 2.6 s.e.). Compared to other phenological observations, the flushing of pine needles occurred over a relatively narrow 22 day period between 15th June and 07th July, when compared to other phenological events in this report. Despite annual variation, the date needles flushed was found to be occurring significantly earlier (1.85 days per year earlier) over the 10 year period ($F(1,8)= 6.896$, $p= 0.03$) (fig 11a))

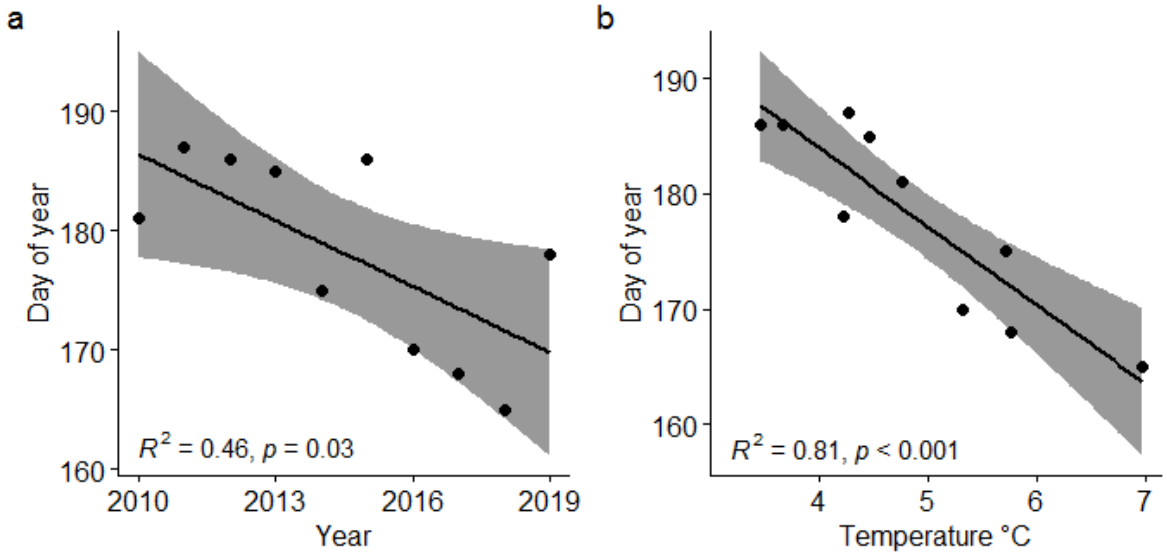

Figure 11 *Date of Pinus sylvestris leaf flushing in the Allt a'Mharcaidh catchment between 2010 and 2019 (a), and relationship between mean May-June temperature (de-seasonalised) and timing of leaf flush (b). Regression lines and 95% confidence limits shown.*

The timing of leaf flush was highly correlated (table 5) with mean May (R= -0.85, p= <.002), June (R= -0.74, p= 0.014), and May-June temperature (R= -0.90, p= <0.001), with peak flush occurring 6.8 days earlier for every 1°C rise in mean May-June temperature (F(1/8)= 33.09, p= <0.001; fig 11b). No further significant relationships were found with any other temperature variable, including heat sums which has widely been used for bud-burst based phenological studies. Although not shown in table 5, no relationships were found between pine flush and monthly or seasonal total precipitation.

Table 5 *Pearson's correlation coefficients for Pinus sylvestris leaf flush and potential temperature drivers for 10 years (2010-2019) in the Allt a'Mharcaidh catchment. Degree days were calculated above a 5°C threshold from 01 February till leaf flush, whilst cold days are the number of days < 5°C from 01 November until leaf flush..*

		Year	Date of pine flush
Year		-	
Date of pine flush		-0.68*	-
Mean temperature:	Jan	0.01	-0.32
	Feb	0.38	0.11
	Mar	-0.03	0.11
	Apr	-0.03	0.08
	May	0.42	-0.85**
	Jun	0.33	-0.74*
	Mar-Apr	-0.04	0.12
	Apr-May	0.21	-0.43
	May-Jun	0.42	-0.90***
	Mar-May	0.15	-0.26
	Apr-Jun	0.3	-0.62
Degree days >5°C	Feb-Onset	-0.14	0.19
Chill days <5°C	Nov-Onset	-0.37	0.46

* p= < 0.05; ** p= < 0.01; *** p= < 0.001

5 Discussion

Although most phenological events in this study were manually identified, the pixel counting method for heather flowering was also highly successful and offers a robust method of identifying the start, peak and end of flowering season across multiple years. However, the success for heather is partly down to wide changes in the colour spectrum concentrated in the foreground of the images. Attempts to apply methods like this to desirable metrics such as snow days at various altitudinal bands would be more difficult due to the obscuring effects of weather on the higher slopes. Indeed this is why snow patches were chosen as the snow metric, as pinpointing the single date-point for final day of snow presence could be done quickly and easily by eye. Conversely identifying daily snow cover throughout the winter would result in extended periods of 'no data' due to weather or equipment failure. Automated methods were also deemed not applicable to pine growth stages or to the spittle counts, due to the small parts of the photograph that they occupy

The environmental factors influencing the onset of phenological events are rarely singular. However, in our simple linear models greater than 70% of the variance was typically explained by the preceding spring-early summer temperatures alone. Only for the onset of spittlemass did the R^2 fall below this (R^2= 0.58). Our methods therefore appear capture the inherent annual variation in both climate and phenological events and their relationship at the site, and as such provide a reliable and growing long-term bio-indictor dataset for the Allt a'Mharcaidh. The only deviance from this was for the effect of extreme snow events on date of snow-melt, which was discussed in section 3.2.3. Going forward, exploring models with additional explanatory variables may be desirable to improve the predictive accuracy for some events, but model improvements are likely to be minor. The strong relationship found between spring temperatures and phenological events agrees with the considerable body of literature that predicts that warmer springs, as expected under a warming climate scenario, will lead to earlier onset for plant and invertebrate phenological events.

For our data, the annual variability in event dates for biological phenology masked any potential change in temporal trends, with the exception of pine leaf flushing. Whether or not onset of events are currently advancing, the data is limited by the relatively short decadal time-series. A longer time-series will eventually overcome such limitations. Indeed Menzel et al. (2020) has shown that advancement of onset is detected more frequently in multi-decadal time-series. There was, however, little evidence in our data for increased temperature during the spring or summer season which might be expected to drive phenological change. For the duration of the biological data, post 2010, an increase in winter temperature was observed, but this did not appear to relate to any of the phenological events. Almost universally, May and June were the key months for driving biological phenology events. Warmer spring to early-summer temperatures always resulted in advancement of the event date, whilst precipitation played little-to-no part in effecting timing, although it appeared to play a limited role in the duration of peak heather flowering. The reasons behind this remain unclear.

Overall, the use of fixed-point repeat photography to identify multiple phenological events in the Allt a'Mharcaidh appears to be highly successful. This has been demonstrated elsewhere (Andrews et al., 2011), and continues to be a robust method of monitoring phenological change in remote areas. It is however limited in scale to

the area in front of the camera only, and would require multiple cameras in different habitats and at varying elevations to provide a more wide-scale phenological change assessment.

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8 Supplementary material

S1 – Heather flowering correlation table

*Pearson correlation coefficients for the dates of heather (Calluna vulgaris) flowering onset, mid-flowering point, and duration of peak flowering season against a range of mean monthly and seasonal temperature periods (de-seasonalised using STL decomposition) and total precipitation. Significant correlations marked with *, with strongest for each phenological event highlighted in bold.*

					Mean Temperature									Total precipitation							
	Year	Onset	Mid	Peak duration	May	Jun	Jul	Aug	MJ	JJ	JA	MJJ	JJA	May	Jun	Jul	Aug	MJ	JJ	JA	MJJ
Flowering Onset	-0.35																				
Mid flowering date	-0.31	0.78**																			
Peak flowering duration	-0.03	-0.03	0.59																		
Temp. May	0.42	**-0.83****	-0.79**	-0.15																	
Temp. Jun	0.33	-0.59	-0.83**	-0.55	0.59																
Temp. Jul	0.46	-0.55	-0.68*	-0.42	0.25	0.66*															
Temp. Aug	0.53	0.29	-0.03	-0.38	-0.15	-0.11	0.3														
Temp. MJ	0.42	-0.80**	-0.91***	-0.38	0.91***	0.88***	0.49	-0.15													
Temp. JJ	0.44	-0.62	-0.82**	-0.52	0.44	0.88***	0.94***	0.14	0.72*												
Temp. JA	0.58	-0.34	-0.57	-0.49	0.14	0.5	0.93***	0.63	0.34	0.81**											
Temp. MJJ	0.5	-0.80**	**-0.94*****	-0.45	0.73*	0.91***	0.81**	0.04	0.91***	0.93***	0.67*										
Temp. JJA	0.56	-0.49	-0.77**	-0.59	0.36	0.78**	0.95***	0.4	0.62	0.96***	0.93***	0.87**									
Precip May	0.16	0.24	0.5	0.44	-0.58	-0.55	0.12	0.35	-0.63*	-0.18	0.23	-0.37	-0.07								
Precip Jun	0.35	-0.18	0.17	0.58	0.22	-0.2	-0.17	-0.02	0.03	-0.2	-0.15	-0.06	-0.19	0.24							
Precip Jul	-0.33	0.65*	0.80**	0.48	-0.52	-0.65*	-0.80**	-0.1	-0.65*	-0.81**	-0.69*	-0.82**	-0.77**	0.29	0.06						
Precip Aug	-0.03	-0.2	0.27	0.63*	-0.19	-0.09	0.05	-0.5	-0.16	-0.01	-0.15	-0.08	-0.15	0.47	0.4	0.15					
Precip MJ	0.3	0.08	0.46	0.63	-0.31	-0.51	0	0.24	-0.45	-0.24	0.09	-0.31	-0.15	0.86**	0.70*	0.25	0.56				
Precip JJ	0	0.35	0.69*	0.72*	-0.23	-0.59	-0.68*	-0.08	-0.45	-0.71*	-0.59	-0.63	-0.68*	0.37	0.70*	0.75*	0.37	0.64*			
Precip JA	-0.2	0.18	0.63	0.75*	-0.42	-0.41	-0.38	-0.44	-0.46	-0.43	-0.48	-0.49	-0.52	0.52	0.34	0.64*	0.86**	0.56	0.68*		
Precip MJJ	0.09	0.36	0.72*	0.71*	-0.48	-0.69*	-0.36	0.15	-0.65*	-0.55	-0.23	-0.61	-0.47	0.81**	0.58	0.64*	0.51	0.90***	0.84**	0.73*	
Precip JJA	-0.02	0.08	0.57	**0.82****	-0.25	-0.4	-0.37	-0.36	-0.36	-0.42	-0.44	-0.42	-0.49	0.51	0.66*	0.53	0.84**	0.72*	0.82**	0.93***	0.81**

* p= < 0.05; ** p= < 0.01; *** p= < 0.001

S2 – Heather flowering curves

GAM generated flowering curves using pixel count of a determined colour range range (RGB [0.7, 0.1, 0.7] ±30%). Peak flowering period is highlighted in red and is calculated as the difference between 25th and 75th percentiles of flowering curve. The mid-flowering point (50th percentile) is also shown.